Toward adaptive x-ray telescopes

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Abstract

Future x-ray observatories will require high-resolution (< 1″) optics with very-large-aperture (> 25 m^2) areas. Even with the next generation of heavy-lift launch vehicles, launch-mass constraints and aperture-area requirements will limit the surface areal density of the grazing-incidence mirrors to about 1 kg/m^2 or less. Achieving sub-arcsecond x-ray imaging with such lightweight mirrors will require excellent mirror surfaces, precise and stable alignment, and exceptional stiffness or deformation compensation. Attaining and maintaining alignment and figure control will likely involve adaptive (in-space adjustable) x-ray optics. In contrast with infrared and visible astronomy, adaptive optics for x-ray astronomy is in its infancy. In the middle of the past decade, two efforts began to advance technologies for adaptive x-ray telescopes: The Generation-X (Gen-X) concept studies in the United States, and the Smart X-ray Optics (SXO) Basic Technology project in the United Kingdom. This paper discusses relevant technological issues and summarizes progress toward adaptive x-ray telescopes.

Key words: X-ray telescopes, x-ray optics, adaptive optics, piezoelectric devices

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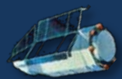
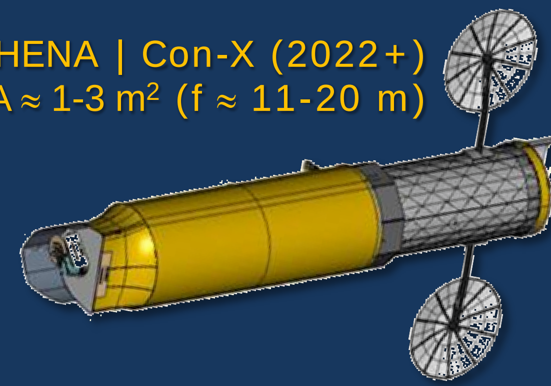
Astronomical x-ray telescopes need large area and high-resolution imaging.

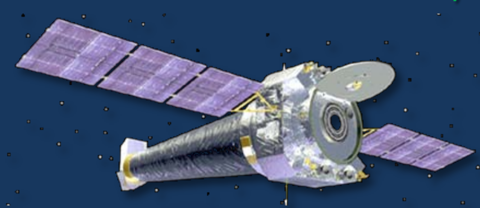


Einstein Observatory (1978-1981)
HPD =10″, A = 0.04 m^2 (f = 3.3 m)

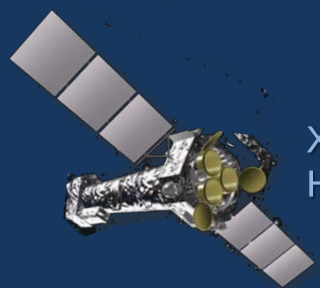
IXO | ATHENA | Con-X (2022+)
HPD = 5″-10″, A ≈ 1-3 m^2 (f ≈ 11-20 m)



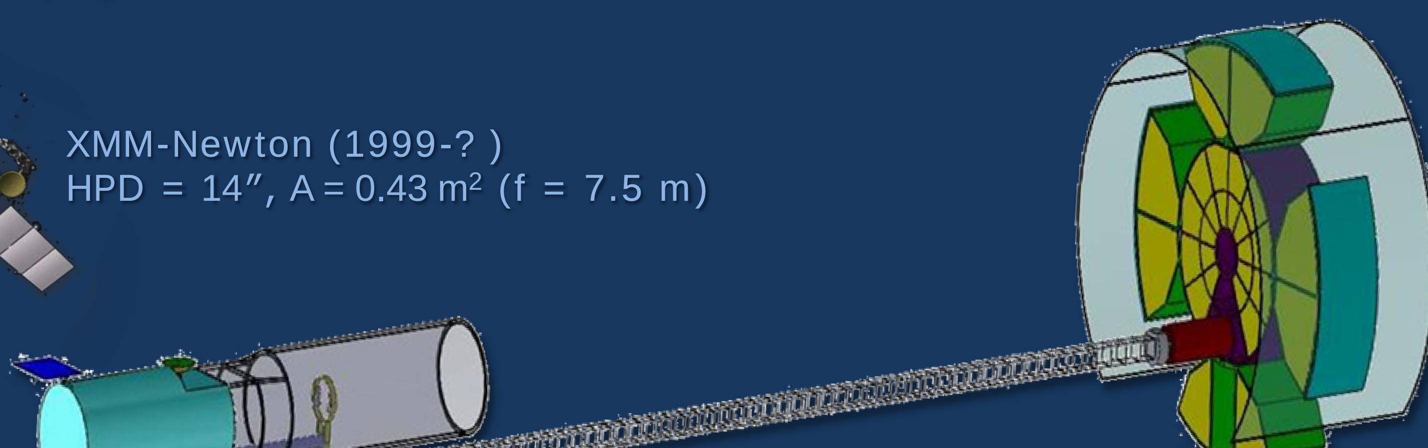
ROSAT (1990-1999)
HPD = 5″, A = 0.10 m^2 (f = 2.4 m)



Chandra X-ray Observatory (1999-?)
HPD = 0.6″, A = 0.11 m^2 (f = 10 m)

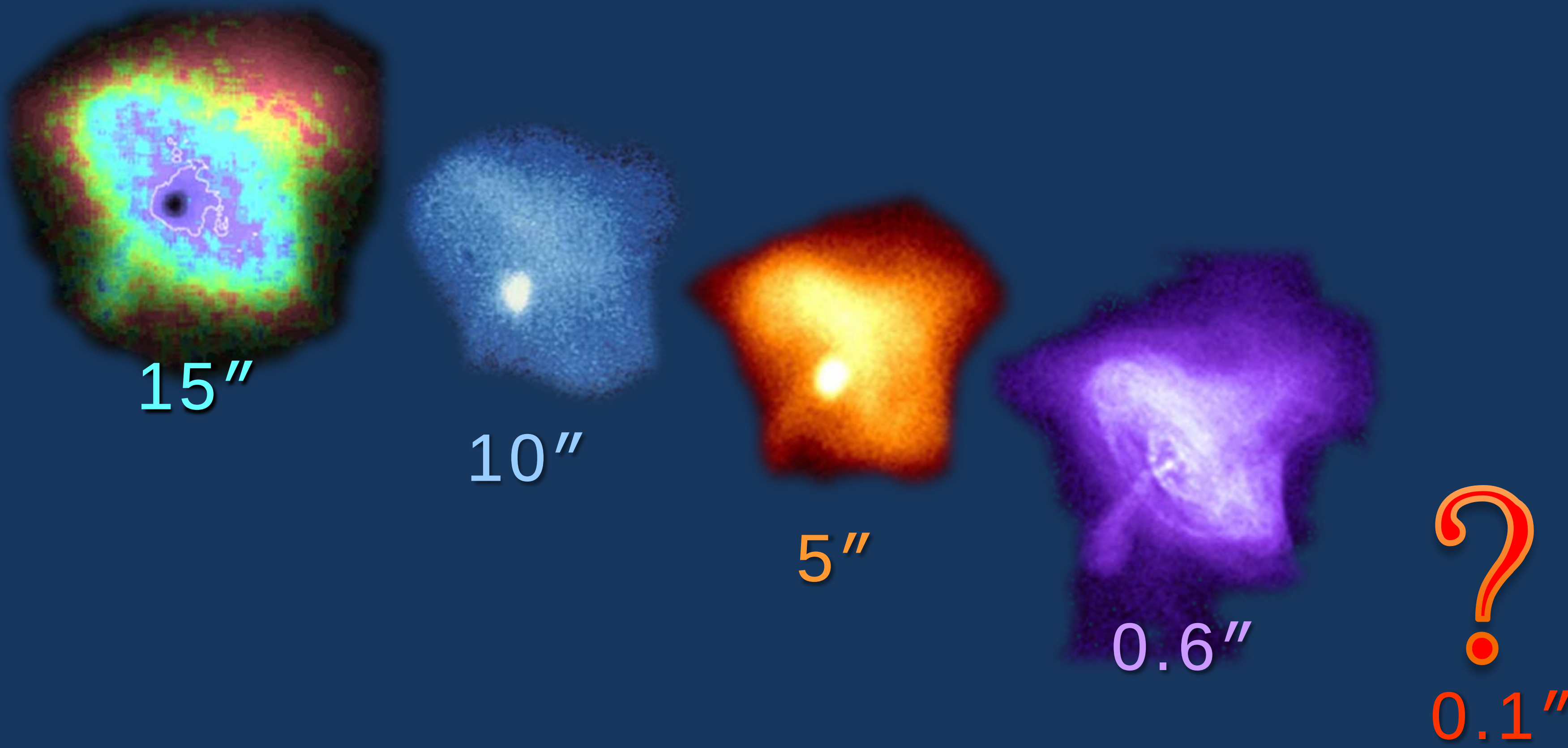


XMM-Newton (1999-?)
HPD = 14″, A = 0.43 m^2 (f = 7.5 m)



Generation-X (2035+)
HPD = 0.1″-1″, A ≈ 5-50 m^2 (f ≈ 20-60 m)

Higher resolution improves both imaging quality and sensitivity (noise reduction).

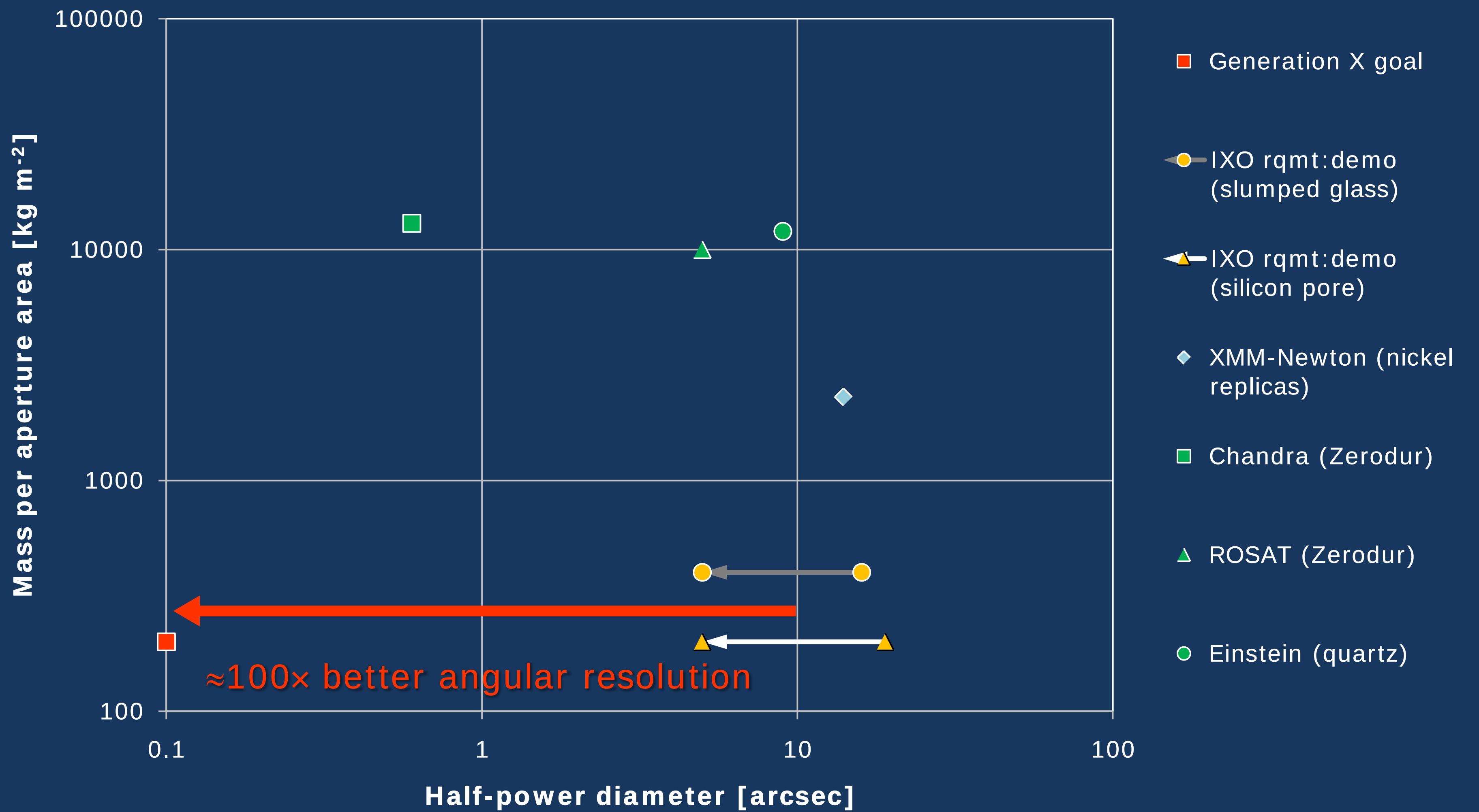


Aperture area improves sensitivity (signal increase), down to the confusion limit.

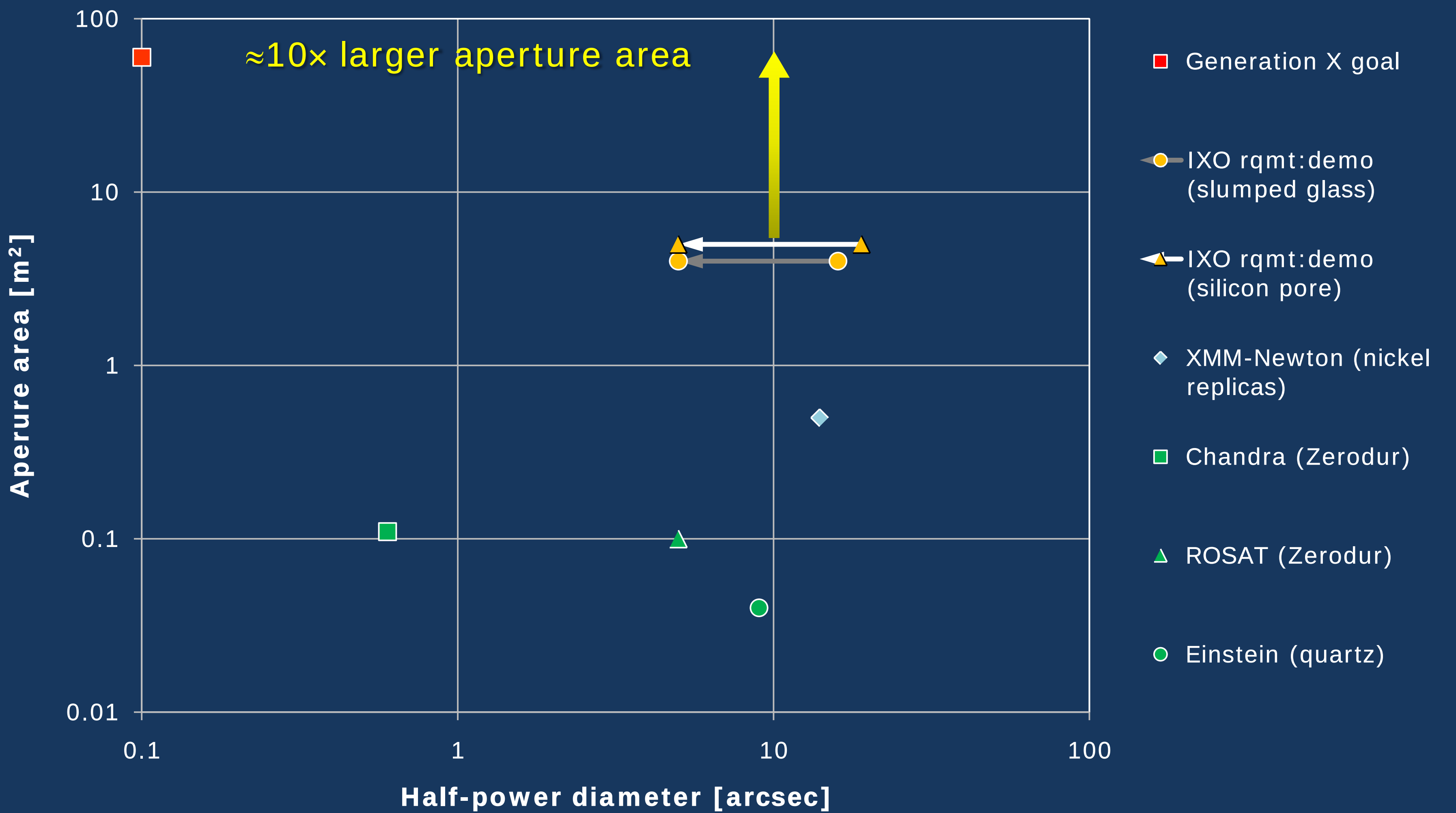
X-ray optics for in-space applications have some unique requirements.

- The standard metric for image quality is the half-power diameter (HPD) = half-energy width (HEW).
  - If axial-slope deviations (σ_α RMS) dominate and are gaussian, then HPD = $1.35 \times 2(\sqrt{2})\ \sigma_\alpha = 3.82\ \sigma_\alpha$.
  - Here “high-resolution” means HPD < 15” ($\sigma_\alpha < 19\ \mu$r).
  - Generation-X goal is HPD < 0.1” ($\sigma_\alpha < 0.13\ \mu$r).
- Science objectives call for large aperture areas A_{ap}.
  - At grazing angle α, mirror surface area $A_{surf} \approx (2/\alpha)A_{ap}$.
  - Achieving this area requires highly nested shells.
  - Mass and volume limitations then require very thin, lightweight mirrors (1 kg/m^2), which easily distort.
  - High degree of nesting leaves no room for reaction structures for active optics $\Rightarrow$ thin-film bimorphs.

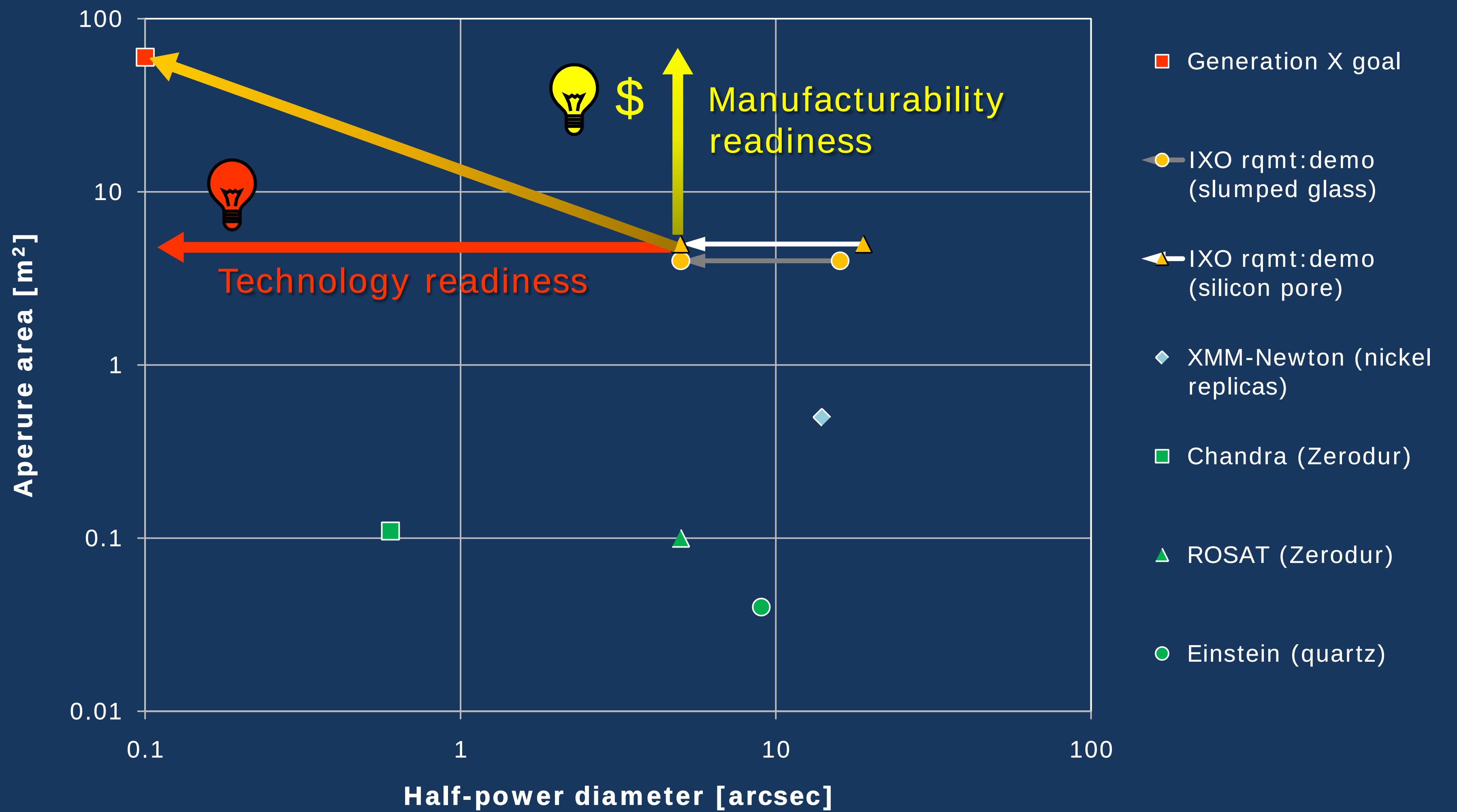
The aperture areal-mass constraint for Generation X is similar to that of IXO.



The aperture-area requirement for Generation X more than 10× that of IXO.



In principle, some segmented optics may be scalable to arbitrarily large areas.



Programmatic constraints require innovation for manufacturing readiness.

- Optimize mandrel fabrication and replication.
  - Minimize post-replication corrections.
- Automate all processes as fully as possible.
  - Implement closed-loop fabrication & metrology.

10000 m^2
0.1-μrad (RMS)
mirror surfaces

Mass constraint
Total mirror mass
≤ 10 tonne

Monetary constraint
Total mirror cost
≤ 0.5 G$

Schedule constraint
Mirror fabrication time
≤ 4 years

Mirror areal density
≤ 1 kg/m^2

Mirror areal cost
≤ 50 k$/m^2

Production rate
≥ 8 m^2/day

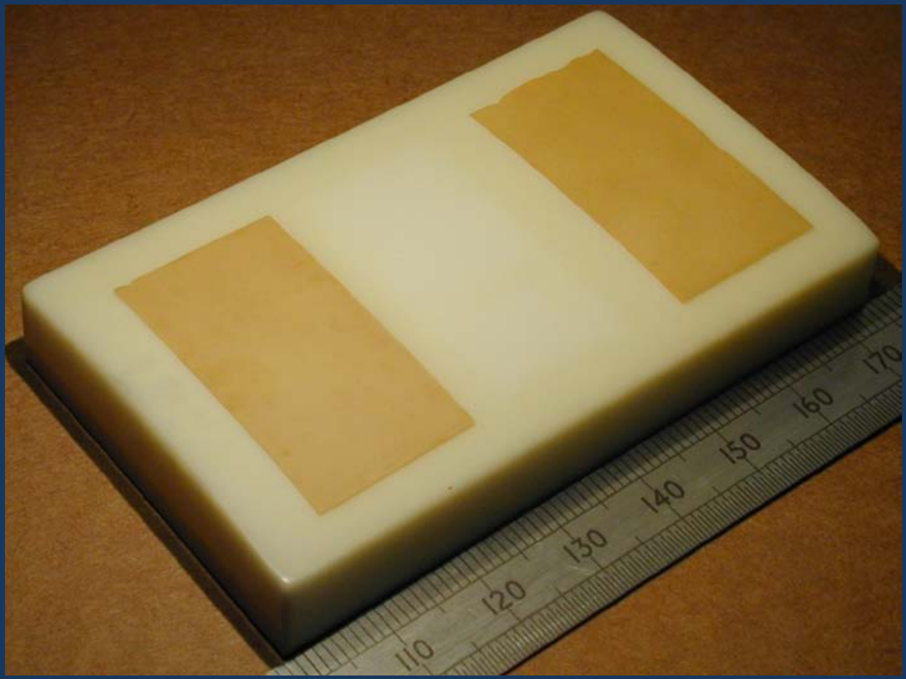
Summary

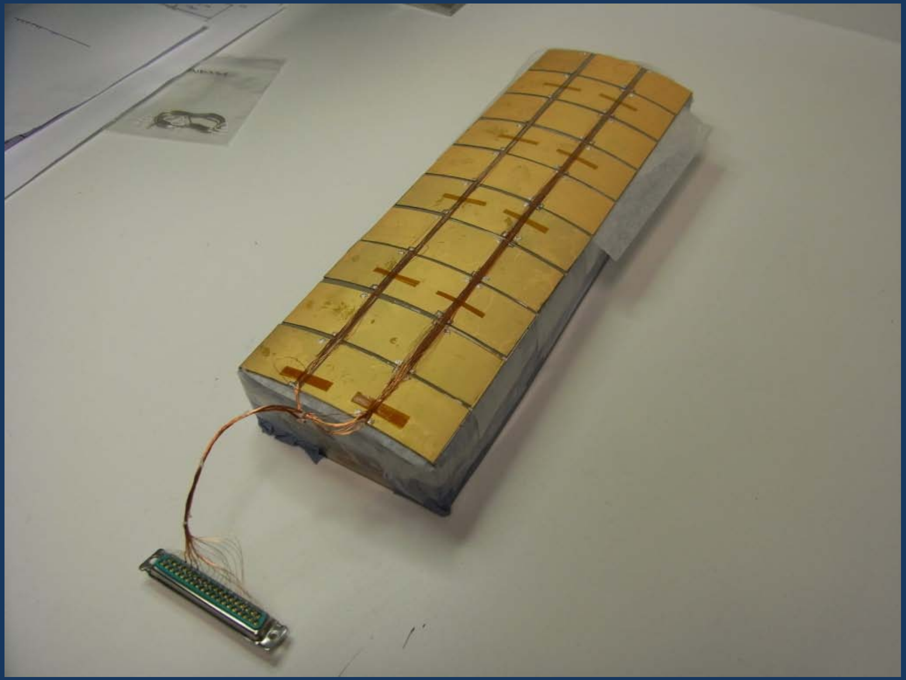
- Fundamental needs for future x-ray telescopes
  - Sharp images $\Rightarrow$ excellent angular resolution.
  - High throughput $\Rightarrow$ large aperture areas.
- Generation-X optics technical challenges
  - High resolution $\Rightarrow$ precision mirrors & alignment.
  - Large apertures $\Rightarrow$ lots of lightweight mirrors.
- Innovation needed for technical readiness
  - 4 top-level error terms contribute to image size.
  - There are approaches to controlling those errors.
- Innovation needed for manufacturing readiness
  - Programmatic issues are comparably challenging.

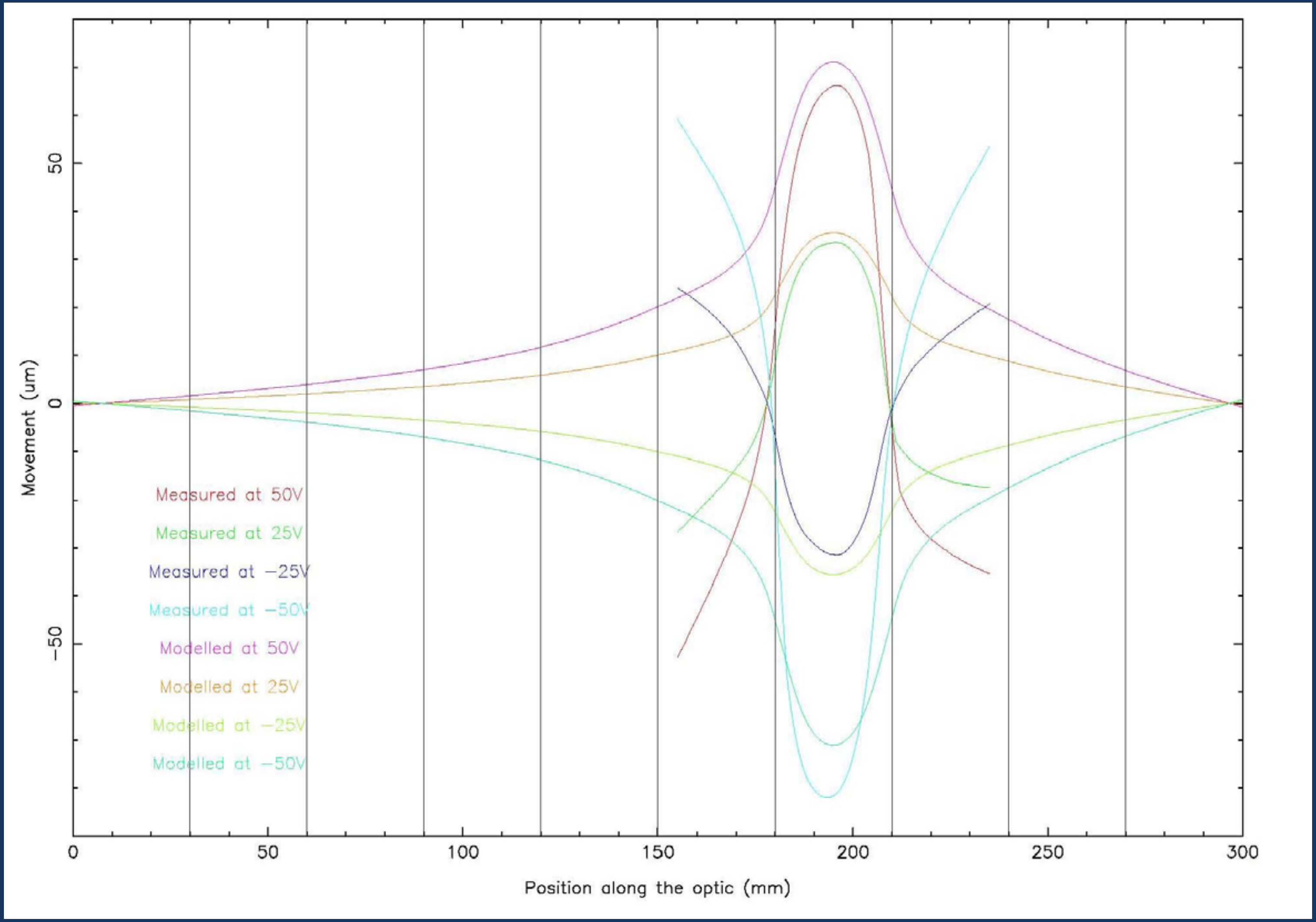
Smart X-ray Optics (SXO) consortium

- Funding
  - UK Engineering and Physical Sciences Research Council (EPSRC), Basic Technologies Grant
- Current members of the SXO consortium
  - University College London (UCL)
  - King's College London (KCL)
  - Scottish Microelectronic Centre (SMC)
  - University of Leicester (UoL)
  - University of Birmingham (UoB)
  - Daresbury Laboratory (DL)
  - Diamond Light Source [Associate member]
  - Silson Limited [Associate member]

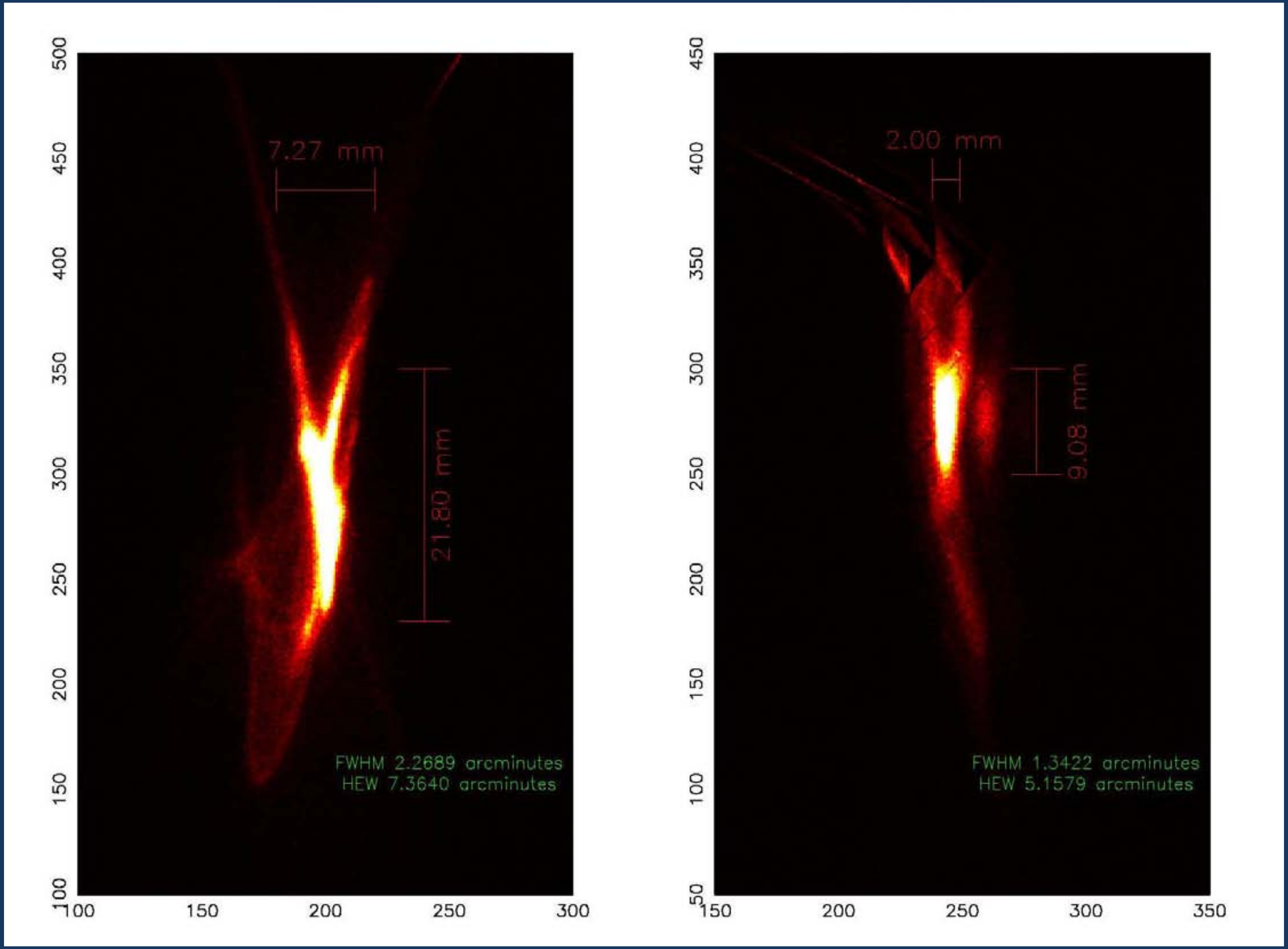
Shaped piezoelectric pads, glued to back of mirror, modify the mirror's figure.

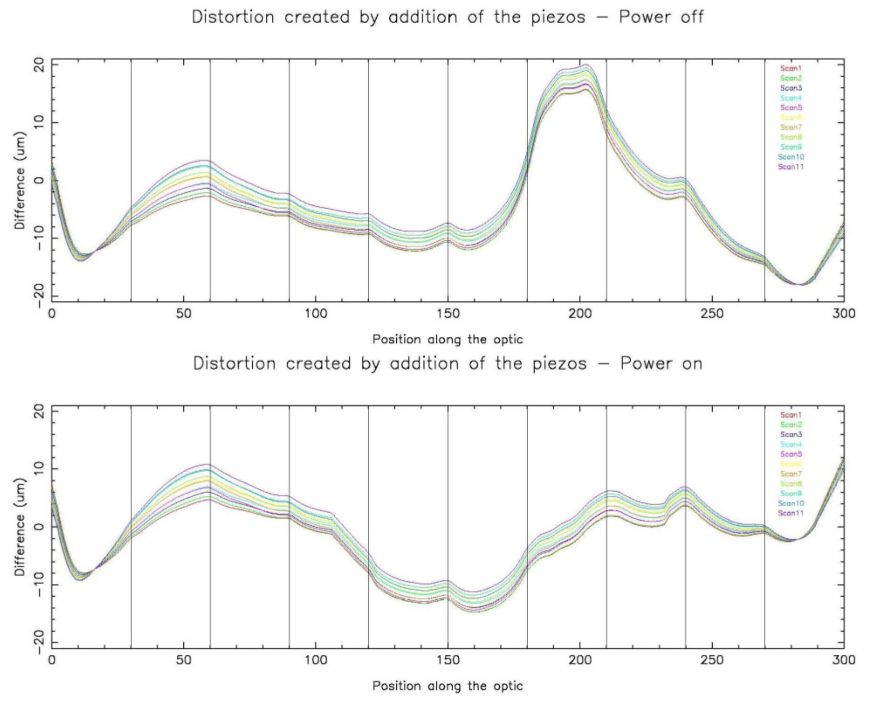


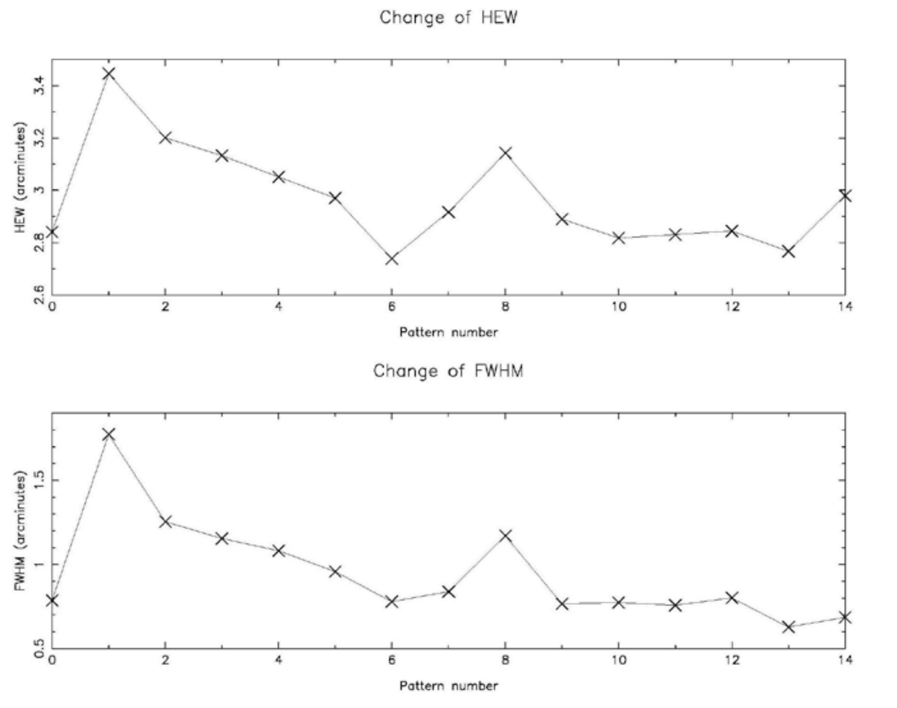




Movement (um)
50
0
−50
Measured at 50V
Measured at 25V
Measured at −25V
Measured at −50V
Modelled at 50V
Modelled at 25V
Modelled at −25V
Modelled at −50V
0
50
100
150
200
250
300
Position along the optic (mm)

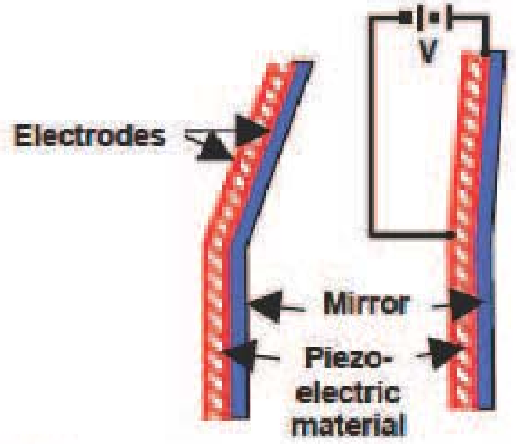

7.27 mm
21.80 mm
FWHM 2.2689 arcminutes
HEW 7.3640 arcminutes
2.00 mm
9.08 mm
FWHM 1.3422 arcminutes
HEW 5.1579 arcminutes

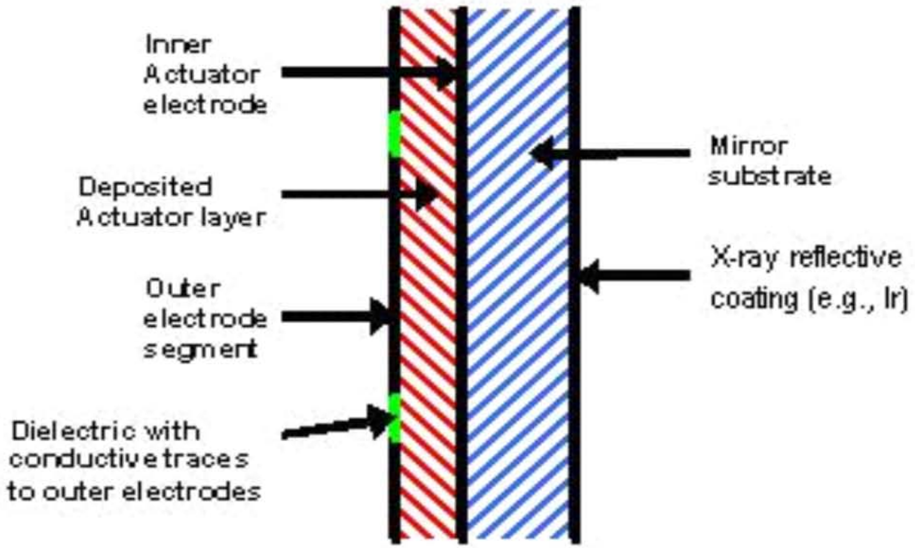

Distortion created by addition of the piezos – Power off
Difference (um)
Position along the optic
Distortion created by addition of the piezos – Power on
Difference (um)
Position along the optic

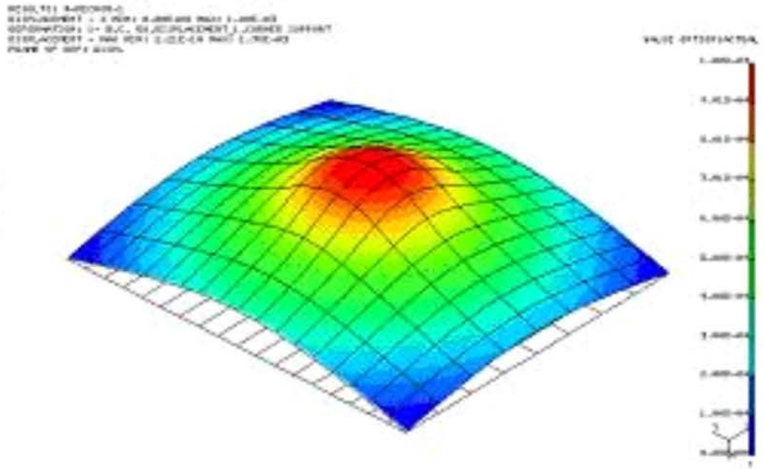

Change of HEW
HEW (arcminutes)
Pattern number
Change of FWHM
FWHM (arcminutes)
Pattern number

Generation-X Adjustable X-ray Optics team

- Funding
  - National Aeronautics and Space Administration (NASA)
    - Vision and Astrophysics Strategic mission concept studies
    - Technology development
  - Gordon and Betty Moore Foundation
- Principal members of the Gen-X optics team
  - Smithsonian Astrophysical Observatory (SAO)
  - NASA Marshall Space Flight Center (MSFC)
  - NASA Goddard Space Flight Center (GSFC)
  - Pennsylvania State University (PSU)
  - Northrop-Grumman [Industrial collaborator]


V
Electrodes
Mirror
Piezo-
electric
material


Inner
Actuator
electrode
Deposited
Actuator layer
Outer
electrode
segment
Dielectric with
conductive traces
to outer electrodes
Mirror
substrate
X-ray reflective
coating (e.g., Ir)

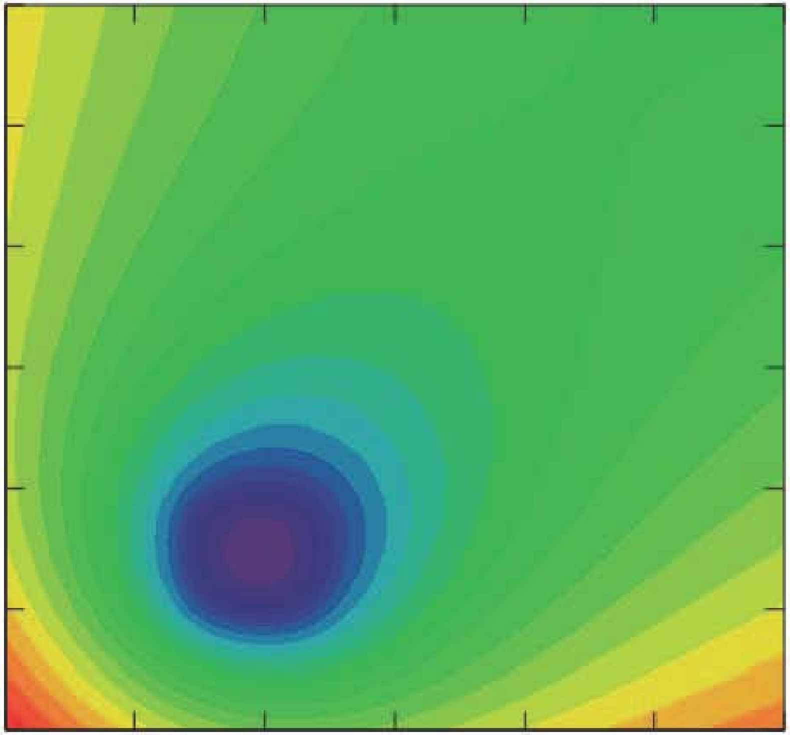


SAO

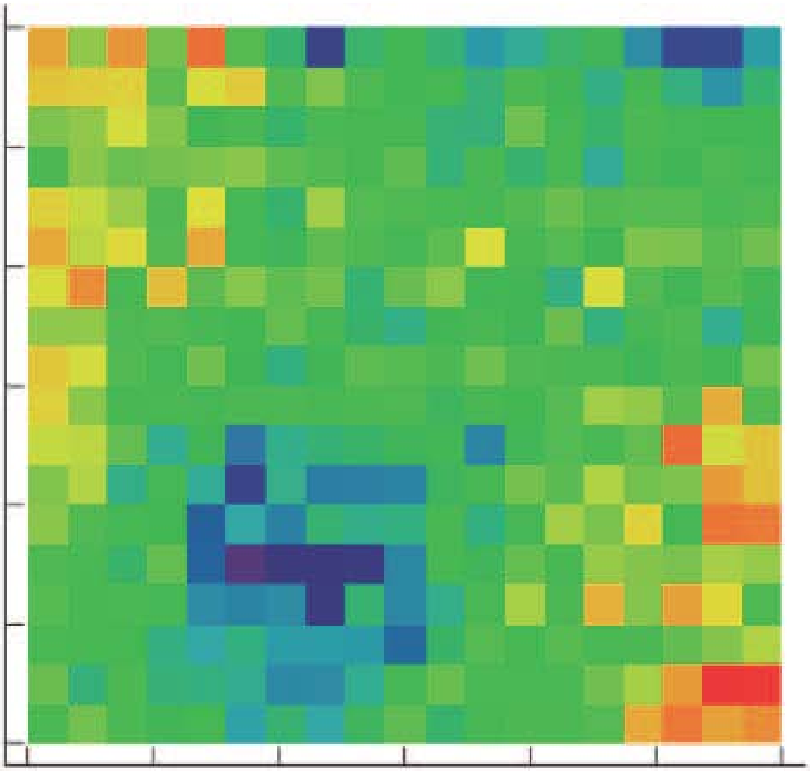
Normalized modeled and measured influence functions

SAO

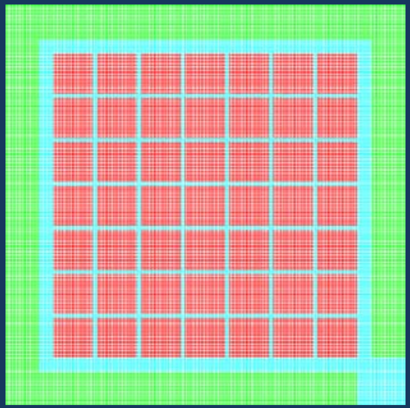
Single piezo cell energized

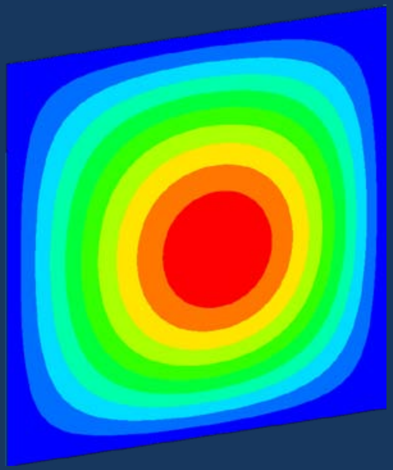


FE modeled



Measured





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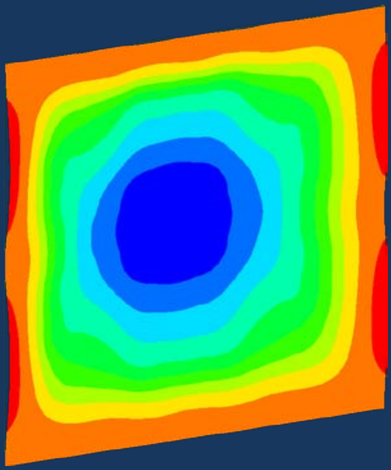

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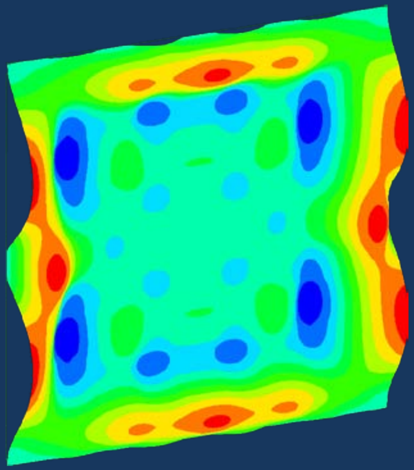

SAO

- **Investigate feasibility of one time, on-ground only figure correction**
  - Examine magnitude of gravity release for a candidate mirror design (2 m diameter, 20 m focal length, 200 mm long mirror segments, 12 point mirror support)
  - Look at amplitude of error and ability to correct gravity release using 1 cm sized piezo cells
  - RMS slope error
    - before – 0.105 arc sec
    - after – 0.010 arc sec